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Short Contribution

Evaluating Mixing Height Estimations in the Western United States Using Satellite Observations

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ABSTRACT

Wildfire smoke can be transported far from its origin, adversely impacting human health. The height of the atmospheric mixing layer, the near-surface layer of the troposphere in which turbulent convection leads to vertical mixing, is called the mixing height. Mixing height is a critical input in the smoke dispersion and air quality models used by agencies that monitor wildfires and air pollution. These models, coupled with forecaster expertise, are also used to determine if it is safe to execute a prescribed burn. In this paper, we derive mixing heights from two satellite datasets in order to assess mixing height forecasts produced by the National Weather Service (NWS) Fire Weather Program. Namely, we use Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) Vertical Feature Masks (VFM) and vertical water vapor profiles from the Moderate Resolution Imaging Spectroradiometer (MODIS). Our comparison indicates that NWS forecasts tend to underestimate CALIOP mixing heights with a median relative error of –13% and a mean relative error of –3.34%. Although MODIS and NWS mixing heights showed some agreement below 3 km, the lower vertical resolution of the MODIS estimates hindered a full comparison. We examine the discrepancies among mixing heights over wildfire smoke plumes determined by these methods and discuss biases and limitations. This work provides insight into potential bias patterns present in current mixing height forecasts and provides directions for future improvements in both NWS mixing height forecasts and satellite-based measurements of mixing height.

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1. Introduction

Wildfire events in the western United States have increased in frequency due to changes in climate, growth of wildland-urban interfaces, severe droughts, invasive species, and historic land management practices such as fire suppression (Dennison et al. 2014; Radeloff et al. 2018; Weber and Yadav 2020). Wildfire smoke has been linked to decreased plant primary productivity (Yue and Unger 2018) and is known to have adverse effects on human respiratory health, particularly in older adults and those with underlying conditions such as asthma and chronic obstructive pulmonary disease (Reid and Maestas 2019).

Air quality forecasts are routinely used to provide health advisories to the public. Government agencies engaged in fire management use air quality models to determine the safety of a prescribed burn. These controlled fires can substantially reduce fuel loads and limit the spread of future wildfires (Williamson et al. 2016). However, air quality concerns are a hurdle in prescribed burn implementation (Sneeuwjagt et al. 2013). Land management agencies base their prescribed burn recommendations on air quality predictions, which are informed by smoke dispersion forecasts. If atmospheric conditions are such that a prescribed burn is expected to adversely impact air quality, the burn will be canceled or rescheduled.

One key input for smoke dispersion forecasting is mixing height, the top of the convective boundary layer below which thermals lead to turbulent convection and vertical mixing (Stull 1988). Lower mixing heights imply slower dispersion of fine particulate matter, leading to worse surface-level air quality and, therefore, canceled prescribed burns (Murthy et al. 2020). National Weather Service (NWS) offices categorize smoke dispersal according to ventilation rates calculated as a product of transport wind and mixing height. Here, mixing height inputs are generated by the National Blend of Models (NBM) using a modified Stull method, which considers moist parcel buoyancy and nonlocal fluxes in the calculation of stability (Craven et al. 2020). Given that mixing height is difficult to reliably estimate and previous researchers have found that NBM forecasts often differ from radiosonde-derived mixing height observations (Schlatter et al. 2018), potential inaccuracies in model-based air quality predictions could impact burn decisions. In other words, inaccuracies in mixing height forecasts could lead to prescribed burns conducted when it is hazardous to do so, or canceled burns at times that do not pose health risks.

Earth-observing satellite instruments, such as Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard the Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) satellite and Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua and Terra satellites, offer a more direct approach to estimating mixing heights than current NWS operational methods. This study extends previous research by contributing a novel evaluation of NWS mixing height estimation practices. We conducted a comparative analysis of NWS Fire Weather Program forecasts and satellite-based estimates using smoke plumes from wildfire events identified in July, August, and September from 2006 to 2020 in the western United States.

2. Data and methods

We compare NWS mixing height estimates to tropospheric aerosol plume heights detected by CALIOP and water vapor mixing ratios from MODIS, following the workflow outlined in Fig. 1. We used NASA WorldView with the Terra and Aqua MODIS Corrected Reflectance viewed in true color, MODIS Fires and Thermal Anomalies, and Visible Infrared Imaging Radiometer Suite (VIIRS)/Suomi National Polar-orbiting Partnership (NPP) Fires and Thermal Anomalies layers to identity smoke plumes over the study period (2006–2020) that were intersected by CALIPSO overpasses. Because many transects intersect multiple NWS fire weather zones (FWZs), and different FWZs may issue different mixing height estimates, we counted each transect segment in a FWZ as a separate observation. We created the Mixing Height Estimation Toolbox (MHEST) to process CALIOP and MODIS data for wildfire smoke plumes in the study period. In order to compare NWS and satellite estimates, CALIOP- and MODIS-derived mixing heights were averaged across FWZs or county warning areas (CWAs). The comparisons were performed where there were direct spatial and temporal overlaps between datasets.

a. CALIOP Vertical Feature Mask

Aerosol retrievals from CALIOP follow CALIPSO's sun-synchronous polar orbit on a 16-day cycle, passing over the western United States between

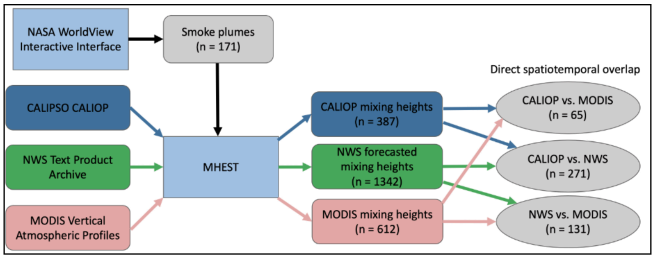

Figure 1. Flow chart showing data collection with the Mixing Height Estimation Toolbox (MHEST) and comparison of mixing heights between datasets. Box colors match those in Fig. 5. *Click image for an external version; this applies to all figures and hereafter.*

2000 and 2100 UTC (Vaughan et al. 2004). Previous studies show that daytime mixing heights derived from the CALIOP instrument are similar to those from radiosonde data and ground-based lidar measurements (Wu et al. 2010; Leventidou et al. 2013; Kim et al. 2021). Here, we use the Version 4.2 Level 2 (L2) CALIOP Vertical Feature Mask (VFM) product (NASA 2018) to determine the maximum altitude of tropospheric aerosols in smoke plumes, which serves as a proxy for mixing height (Fearon et al. 2015). The L2 VFM product is generated from a classification algorithm that utilizes aerosol backscatter, among other parameters, to determine feature types and subtypes, such as aerosol (type) and smoke (sub-type) (Fig. 2). The horizontal resolution is 333 m and the vertical resolution is 30 m within roughly 8 km mean sea level of the Earth's surface (National Aeronautics and Space Administration, 2018). MHEST unpacks and extracts mixing height estimates from the CALIOP VFM granules, using the top aerosol layer as the mixing height. The CALIOP layer heights were converted to kilometers above ground level (AGL). As in Leventidou et al. (2013) and Fearon et al. (2015), we removed elevated and discontinuous aerosol layers for CALIOP observations (Kim et al. 2021). Our definition of an elevated layer (i.e., where the bottom layer is at least 3 km AGL) is higher than that of Leventidou et al. (2013) or Fearon et al. (2015), yet we found the inclusion of more lofted plumes did not significantly alter the results of the study.

b. MODIS atmospheric profiles

We used L2 water vapor and temperature profiles from Terra MODIS as a second method of estimating

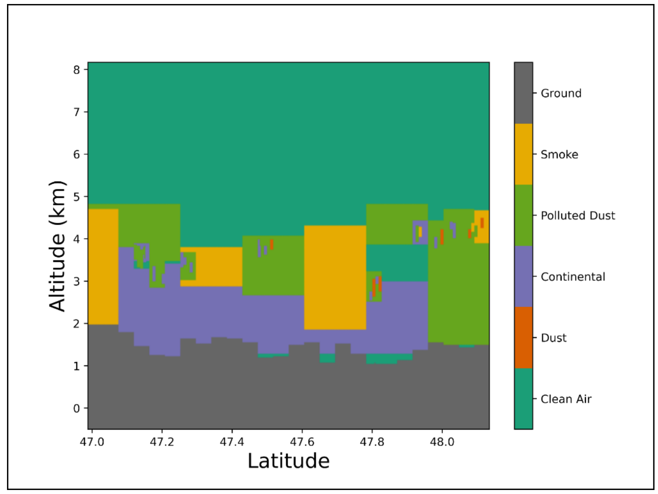

Figure 2. Curtain plot showing a typical CALIOP profile used for analysis. Colors indicate the VFM classified aerosol sub-types. The data were collected over Southern Idaho on 27 August 2015.

mixing height. These data are collected at 20 vertical levels (at 1 km resolution in the troposphere) and 5x5 km grid spacing (Borbas et al. 2016). Following the sounding-validated methods in Feng et al. (2015), MHEST calculates the gradient of the MODIS-measured water vapor mixing ratio and identifies the inflection point in the gradient, marking the initiation of a plateau in the mixing ratio (Fig. 3) and therefore entry into the mixing layer from the free troposphere.

c. National Weather Service spot and fire weather forecasts

The majority of NWS offices in the western and central parts of the United States use NBM outputs in routine mixing height forecasts, called fire weather forecasts (FWFs). Meanwhile, spot forecasts are non-routine, site-specific forecasts issued by Weather Forecast Offices on an ad-hoc basis for a wildfire or prescribed burn that cover a specific location or small geographic area (Lammers and Horel 2014). To make these spot forecasts, NWS offices in the western and central United States use a combination of 1) NBM output, with mixing height calculated using a modified Stull method, 2) balloon sounding data, and 3) individual forecaster expertise. This procedure has not been standardized, so spot forecasting methods and predictions may vary widely between offices. To compare NWS and satellite-derived mixing heights, we acquired these two types of historic NWS mixing

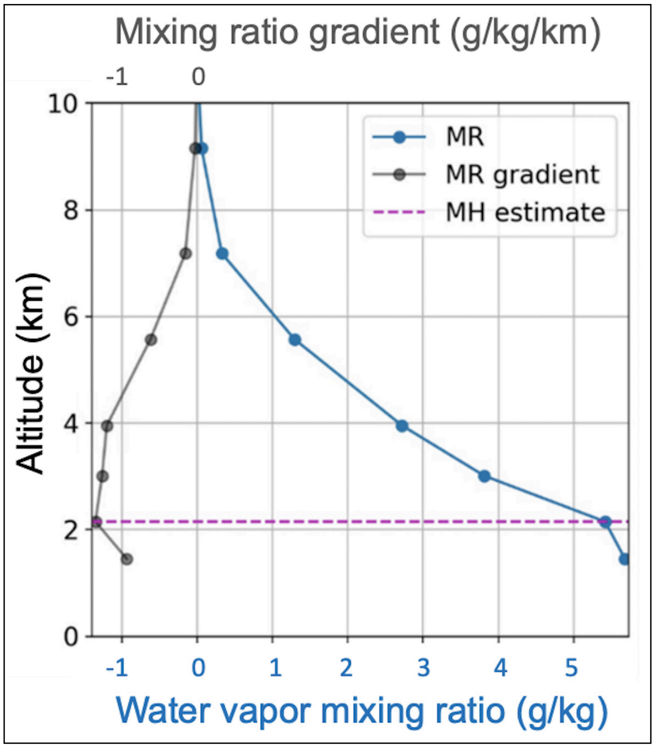

Figure 3. Water vapor mixing ratio (MR) and gradient in the MR used to estimate mixing height (MH) from the 20 August 2020 Terra MODIS atmospheric profile over Eastern Oregon.

height forecasts from Iowa State University's Environmental Mesonet NWS Text Product archive.

3. Analysis and discussion

a. Case study

As a case study, we examined a smoke plume from the Grizzly Complex Fire in the Coeur d'Alene River Ranger District of the Idaho Panhandle National Forests in northern Idaho on 27 August 2015. Smoke from this region was transported at least 25 km northeast as determined by visual analysis using NASA WorldView. The CALIOP data overlapped the active burn area on this date between 47.68 to 47.90°N latitude. The smoke plume detected from 47.25 to 47.41°N latitude likely originates from the Grizzly Complex fire, based on nearby VIIRS thermal anomalies. Some of the smoke may also have been transported from the Marble Creek and Breezy fires further south. CALIOP and MODIS footprints intersected the smoke plume on 27 August 2015 in FWZ ID101 (Fig. 4a). Mixing heights from CALIOP

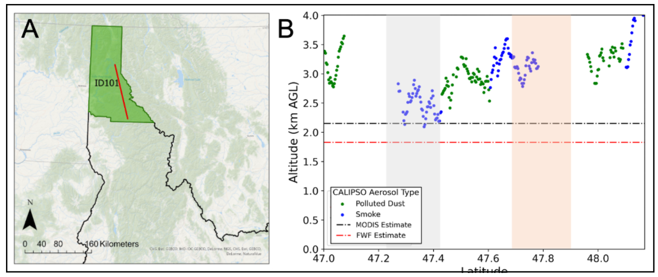

Figure 4. Case study of the Grizzly Complex fires smoke plume event in the Coeur d'Alene River Ranger District of Northern Idaho on 27 August 2015 in fire weather zone (FWZ) ID101. (A) The red line shows the CALIPSO transect within FWZ ID101. (B) Estimated mixing heights for this case study. The CALIPSO transect overlap with the Grizzly Complex fire active burn area is highlighted in orange and the overlap with a smoke plume originating from the Grizzly Complex fire and other fires further south is highlighted in gray.

and MODIS were higher on average than the NWS fire weather forecasted value in FWZ ID101 (Fig. 4b).

b. Campaign-wide comparison

Figure 5 demonstrates similar ranges of mixing height values acquired from CALIOP and the NWS fire weather forecasts while indicating a much narrower, lower distribution of mixing heights for MODIS. MODIS data are restricted to just a few discrete pressure levels due to the limited vertical resolution of the water vapor profiles and produce mixing heights below 3 km AGL across all smoke plumes used in this study. The MODIS mixing height estimation algorithm identifies the lowest inflection point in the water vapor mixing ratio gradient, which represents the transition into the lowest altitude moist layer. Although this point of inflection should correspond to the height of the mixing layer, MODIS may be detecting advected moisture layers lower than the actual mixing height altitude (Feng et al. 2015). Moist layers may be advected to the region by daytime winds rather than formed in situ from local mixing, particularly where maritime breezes are common. Accordingly, many of the lowest mixing height estimates from MODIS occurred in coastal regions.

To evaluate NWS mixing height forecasts, we compared NWS forecasts to MODIS zonal mean mixing heights (Fig. 6a); CALIOP observations to MODIS zonal mean mixing heights (Fig. 6b); and spot forecasts to fire weather forecasts (Fig. 7). As discussed

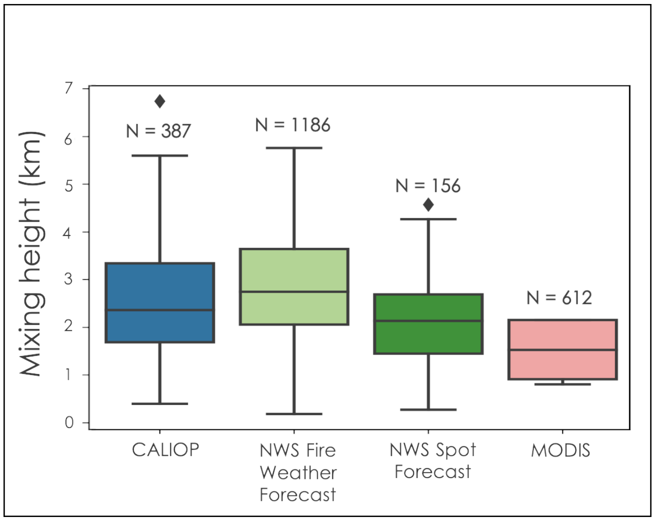

Figure 5. Box plot showing the distribution of mixing heights estimated from each method. The CALIPSO values represent the average mixing heights in FWZs intersecting the plumes. The MODIS values are from 5 x 5 km grids that intersect the plumes. The NWS values are for the whole FWZ or county warning area (spot forecasts) that contains a plume.

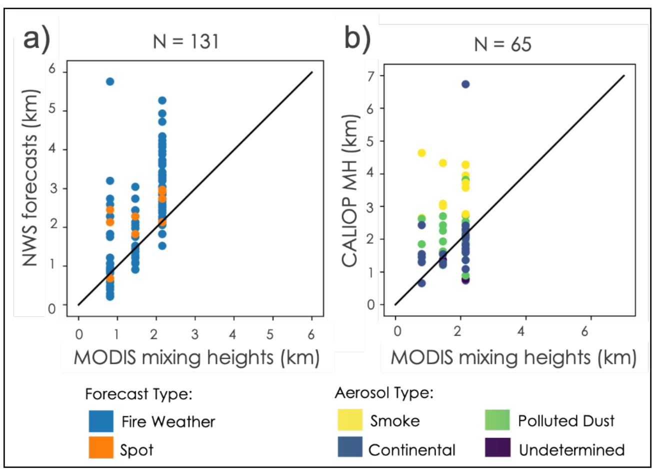

Figure 6. Comparisons of FWZ mean mixing heights between a) NWS forecasts and MODIS and b) CALIOP and MODIS. One-to-one lines indicate perfect coherence between the two compared mixing heights for a smoke plume event.

above, MODIS mixing heights tend to underestimate NWS predictions, although lower NWS mixing heights correlate well with MODIS. Figure 6b shows the smoke aerosols classified by the VFM yield higher mixing heights than the other aerosol types, which diverge further from MODIS estimations. This may be due to the VFM classification algorithm, which uses increased

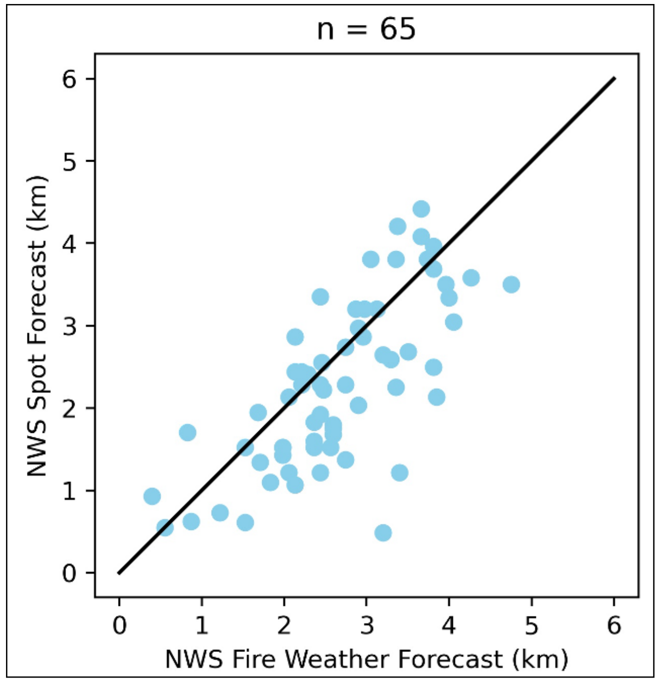

Figure 7. Comparison of the National Weather Service fire weather forecasts (FWF) with their spot forecasts for overlapping events. The one-to-one line indicates perfect coherence between the two compared mixing heights for a smoke plume event.

layer height as a way to distinguish smoke aerosols from other types of aerosols (Kim et al. 2018). We found substantial disagreement between CALIOP and NWS forecasted mixing heights, with a Pearson correlation coefficient of 0.18 (Fig. 8).

We also explored spatial trends in the mixing height comparisons. Relative error across the study area revealed a tendency of the NWS fire weather forecasts to underestimate mixing heights in the Pacific Northwest (Fig. 9). Although adjacent fire weather zones in other states such as Oregon, Idaho, and Wyoming are similarly underestimated, the majority of these relative errors were less extreme. However, the sparseness of the dataset (just 12% coverage across fire weather zones in the study area) limits further interpretation. Mean absolute error (MAE) was calculated for mixing height estimates among the NWS fire weather forecasts, NWS spot forecasts, both NWS forecasts, CALIOP, and MODIS (Table 1). Of the two NWS products, the spot forecasts showed greater agreement with all satellite-derived mixing height observations than with the NWS fire weather forecasts, perhaps because spot forecasts are made on an ad-hoc

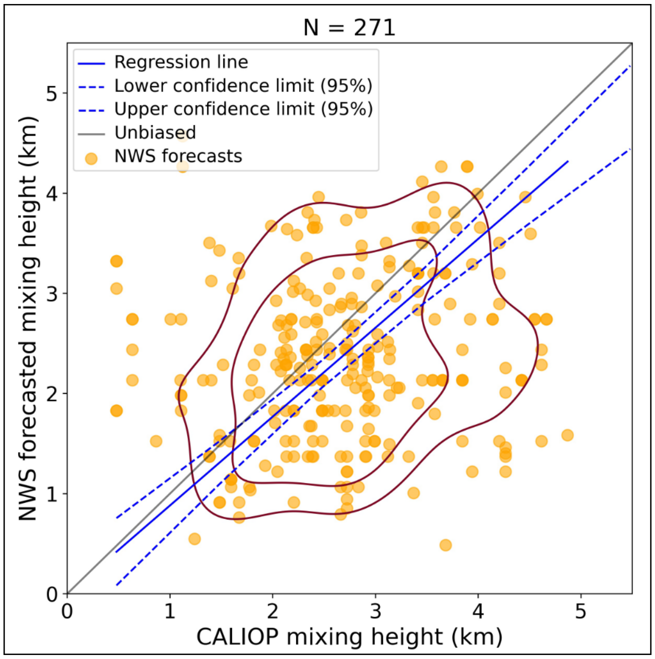

Figure 8. Mean mixing heights from CALIOP versus NWS fire weather and spot forecasts. Contours represent bivariate probability densities greater than 0.04 and 0.08. Orthogonal distance regression gives a slope of 0.91. Pearson's r=0.18.

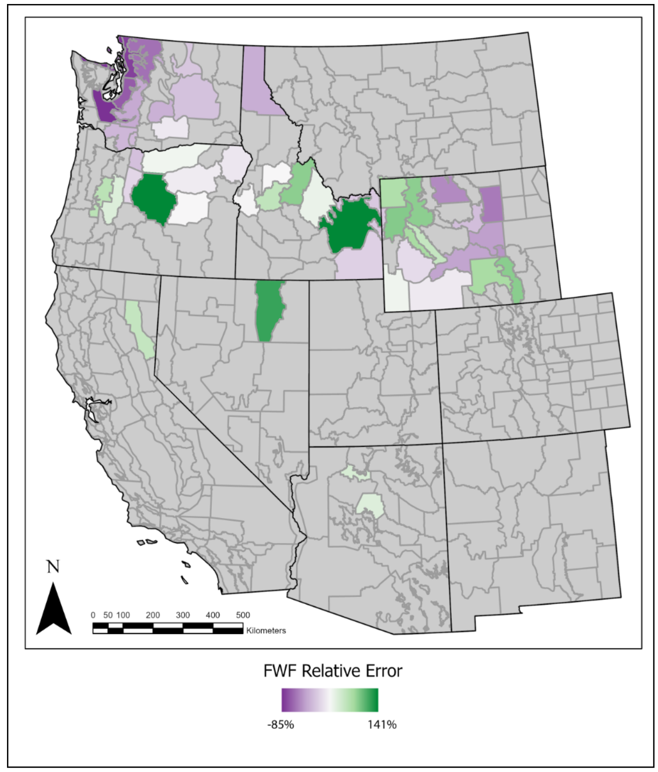

Figure 9. Average percent error of NWS fire weather forecast mixing heights relative to CALIOP observations across the 14-year study period for 51 FWZ. The largest underestimates occurred in Western Washington while the largest overestimates occurred in Southeastern Idaho. Gray FWZ represent 398 zones for which we did not identify any CALIPSO passes over smoke plumes or where NWS mixing height forecasts were not available.

basis for specific fires, and may include effects of surface heating.

Our results support those from previous research. For instance, in their study verifying NWS spot forecasts using atmospheric sounding observations, Nauslar et al. (2016) found mixing height spot forecasts exhibited large MAEs compared to atmospheric soundings and were biased toward erroneously high mixing heights. In comparison to Stull-based atmospheric soundings, spot forecasts exhibited a MAE of 0.618 km for the western United States (Nauslar et al. 2016). We found similar MAEs between spot forecasts and satellite-derived estimates: MODIS (0.72 km) and CALIOP (0.87 km). However, while Nauslar et al. (2016) found spot forecasts overestimated mixing height, we found both spot and fire weather forecasts were consistently lower than CALIOP-derived estimates. The median and mean relative error compared to CALIOP were –13.0% and –3.34%, respectively, suggesting the majority of NWS forecasted mixing heights were much lower than CALIOP estimations. Whereas ad-hoc forecaster adjustments in spot forecasts may account for the impacts of surface heating from a fire that could substantially increase mixing height, fire weather forecasts do not, which likely contributes to the underestimation of mixing height. If we assume that smoke aerosols are classified properly and exclude other types of tropospheric aerosols from this analysis, then the NWS forecasts underestimated CALIOP even more:–33.7 % and –27.1% for the median and mean relative error, respectively. Fearon et al. (2015) found the models undergirding the forecasts tended to underestimate compared to the VFM, and in this study we found the forecasts themselves do the same. Schlatter et al. (2018) also found that the NWS models typically underestimated mixing height in Denver and Grand Junction, Colorado compared to radiosonde data, especially on well-mixed days.

Table 1. Mean Absolute Error (MAE) in mixing height estimates in kilometers above ground level between CALIOP, MODIS, NWS spot forecasts, and NWS fire weather forecasts.

	MODIS	**NWS spot forecast**	**NWS fire weather forecast**	**NWS (all forecasts)**
CALIOP	0.84 (n=65)	0.87 (n=109)	0.97 (n=162)	0.93 (n=271)
MODIS		0.72 (n=11)	0.83 (n=120)	0.82 (n=131)

c. Uncertainties and limitations

The primary limitations of estimating mixing height from CALIOP VFM were the data latency of approximately six months, sparse spatial coverage (limited to <500 m wide transects), and temporal resolution. CALIOP has a revisit interval of ~16 days, which is too infrequent to inform NWS routine forecasts and spot forecasts, which require a minimum of two measurements per day. Such constraints hinder these satellite methods from being operationalized by the NWS for real-time forecasting. Additionally, signal attenuation reduces certainty in lower mixing height estimation, while free troposphere injections of aerosols may have resulted in spurious high estimates (Amiridis et al. 2010). MODIS-derived mixing heights were limited by the vertical resolution of the atmospheric profile data. The algorithm used for analysis of the water vapor mixing ratio profiles did not produce mixing heights above 3 km AGL for the plume events in this study. Future work should assess the capability of the method for estimating mixing heights at higher altitudes.

Meanwhile, historic mixing height observations are limited, and generally restricted to radiosondes or vertical wind profilers. NWS mixing height predictions are also intended for prescribed burn smoke, which may not convect as much as wildfire smoke. Additionally, bias and error may have been introduced in the NWS forecasting process based on selected model data and/or local adjustments made by human forecasters. As noted in Fearon et al. (2015) and Nauslar et al. (2016), the estimation and verification of mixing height is very difficult. Any sounding or profiler data that are used will be sparse and may not apply to an entire fire weather zone (Nauslar et al. 2016), especially in the complex terrain of the western United States. Finally, the nocturnal boundary layer and significant changes in terrain may influence the mixing layer and sounding error within a given zone.

4. Conclusions

We compared National Weather Service (NWS) mixing height forecasts to satellite-based estimates across the western United States, corresponding to 171 wildfire smoke plume events between 2006 and 2020. Similar to previous research, we found mixing height difficult to estimate reliably and to verify (Fearon et al. 2015; Nauslar et al. 2016). Although we did not find strong evidence supporting systematic biases in NWS predictions, we did find substantial differences between NWS forecasts and the mixing heights determined from CALIOP Vertical Feature Mask (VFM) data. The disagreement between these two methods was especially evident at lower mixing heights, which is when accurate forecasts are most important because they constrain authorization of prescribed burns. Compared with CALIOP VFM data, NWS tended to overestimate at lower mixing heights (<2.5 km AGL) and underestimate at higher mixing heights (>3.0 km AGL). Overall, the forecasts predominantly underestimate mixing height, with a median relative error of –13.0% and a mean relative error of –3.34%. This underestimation is consistent with the results reported by Fearon et al. (2015) and Schlatter et al. (2018), who found that the Stull method underlying the forecasts also tended to underestimate mixing height. While mixing heights from MODIS atmospheric profiles generally agreed with NWS forecasts below 3 km AGL, the low vertical resolution of the MODIS data limits further evaluation of the comparison.

The results of this study may help the NWS to identify potential areas for improvement in mixing height forecasts, allowing land managers to conduct prescribed burns under the safest possible conditions and effectively manage resources related to prescribed burning. Furthermore, this study highlights the need for increased coverage and resolution of satellite observations of vertical properties of the atmosphere, and in particular, decreased latency time for aerosol lidar retrievals. Meanwhile, increased vertical resolution for passive water vapor retrievals would enable mixing height forecasts independent of the presence of smoke aerosols. With these improvements, satellite-derived measurements of atmospheric properties could provide valuable data to inform real-time forecasting operations and validate NWS mixing height forecasts. Future research might consider additional variables, such as terrain, wind shear, humidity, and fire radiative power, to determine whether mixing height estimates are more or less accurate in certain environments.

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OPEN RESEARCH

The software associated with this manuscript for the calculation of mixing heights (MHEST) is published on GitHub https://github.com/NASA-DEVELOP/MHEST.